



An Agile Beam Transmit Array Using Coupled Oscillator Phase Control

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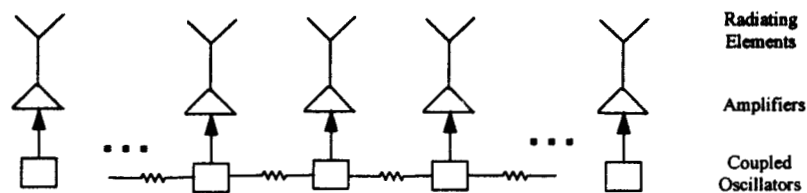
Introduction

- Consider a linear array of coupled oscillators.
 - Achieves high radiated power through coherent spatial power combining.
 - Usually designed to produce constant aperture phase.
- Oscillators are injection locked to each other or to a master oscillator to produce coherent radiation.
- Oscillators do not necessarily oscillate at their tuning frequency.
- Adler has shown that the phase of each oscillator is a function of the difference between the *tuning frequency* and the *oscillation frequency*.
- York, et. al. have shown that the oscillation frequency of the array is the average of the free running frequencies of the oscillators.

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Our purpose in coupling oscillators together is to achieve high radiated power through the spatial power combining which results when the oscillators are injection locked to each other. Adler has shown that the phase of the oscillator output is a function of the difference between the free running frequency and the oscillation frequency. York, et. al. have shown that, left to themselves, the ensemble of injection locked oscillators oscillate at the average of the tuning frequencies of all the oscillators.

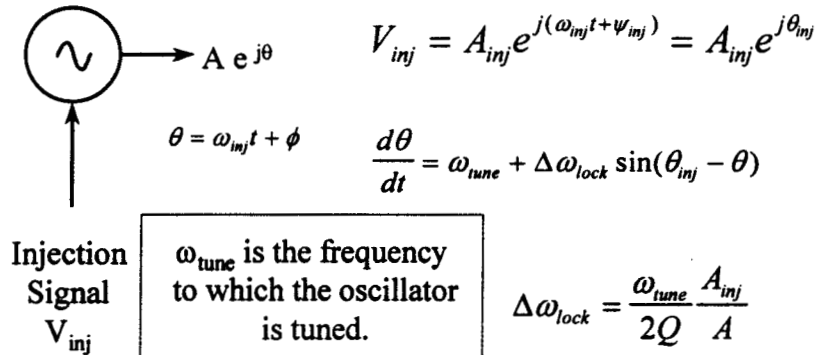
Coupled Oscillators for Radiating Aperture Phase Control



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This shows the concept of controlling the phase in a radiating aperture using coupled electronic oscillators. The amplifiers serve two purposes; they provide for high radiated power and they isolate the oscillators from the parasitic coupling between the radiating elements thus permitting more precise control of the nature of the interoscillator coupling.

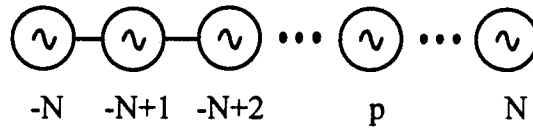
Injection Locking



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Consider a single injection locked oscillator. We represent the signals as complex functions as indicated. In steady state, of course, the oscillator will oscillate at the injection frequency. The transient (time varying) behavior is governed by the indicated differential equation. Using this equation we can formulate the theory of a set of coupled oscillators.

Coupled Oscillators



$$\frac{d\theta_i}{dt} = \omega_{tune} - \frac{\omega_i}{2Q} \sum_{\substack{j=i+1 \\ j \neq i}} \epsilon_{ij} \frac{A_j}{A_i} \sin(\Phi_{ij} + \theta_i - \theta_j)$$

In the continuum model:

$$\nabla^2 \theta - \frac{\partial \theta}{\partial \tau} = - \frac{\omega_{tune}}{\Delta \omega_{lock}}$$

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Here we adapt the preceding differential equation to describe the behavior of a linear array of coupled oscillators with nearest neighbor coupling. Using a continuum model of this description leads to the partial differential equation shown at the bottom of the vugraph. Tau is time multiplied by the locking bandwidth of the oscillators.

The Finite Array (Continued)

It should be noted that the time constants in the dynamic solution are given by the eigenvalues. The slowest time constants are:

$$\sigma_{\min} \approx \left(\frac{\pi}{2a+1} \right)^2 \quad \text{for nonsymmetrical detuning}$$

$$\sigma_{\min} \approx \left(\frac{2\pi}{2a+1} \right)^2 \quad \text{for symmetrical detuning}$$

In both cases the response time is proportional to the *square* of the number of oscillators in the array.

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A significant result of this analysis is that the response time of such an array is proportional to the square of the number of oscillators. This is apparently a well known result in diffusion theory and arises here because the differential equation governing the phase dynamics is of diffusion type.

Beamsteering Dynamics

Equal and opposite detuning of the end oscillators; i.e.,

$$\Delta\omega_L = -\Delta\omega_R = \Delta\omega_T$$

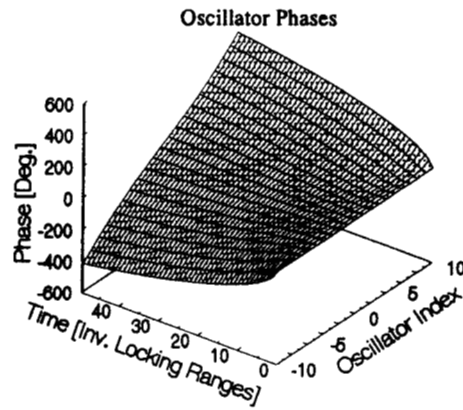
yields,

$$\phi(x, \tau) = \frac{\Delta\omega_T}{\Delta\omega_{lock}} \sum_{m=0}^{\infty} \frac{2 \sin(b\sqrt{\sigma_m}) \sin(x\sqrt{\sigma_m})}{(2a+1)\sigma_m} (1 - e^{-\sigma_m \tau})$$

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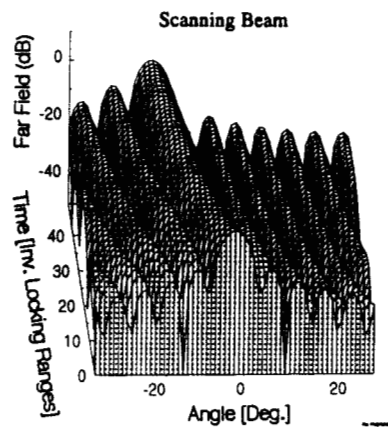
According to Liao, et.al. [IEEE Trans. MTT-41, pp. 1810-18115, Oct. 1993], beamsteering is accomplished by equal and opposite detuning of the end oscillators of the array. The solution for the phase distribution can be obtained from the solution for detuning one arbitrary oscillator ($x=b$) by superposition (subtraction) of two solutions, one for $b=a$ and one for $b=-a$. The time domain result is as shown.

Beamsteering Phase



This is a graphical representation of the beamsteering phase solution just obtained.

Far Zone Radiation Pattern



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This plot shows the dynamics of the far zone radiation pattern during beamsteering. It was obtained by computing the radiation pattern for each time value by integration over the aperture using the phase solution represented on the previous vugraph. Note that the beam integrity and sidelobe structure is maintained throughout the transient period.

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PM 2503 MMIC

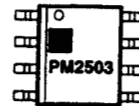


PM2503 DATA SHEET

RFIC OSCILLATOR 2000 to 3000 MHz Operation

Features

- 3 - 5 Volt Single Supply
- Output Power 14 dBm @ 5V
- Low Cost Surface Mountable
- Buffered AC Coupled Output



SO-8 Plastic Package

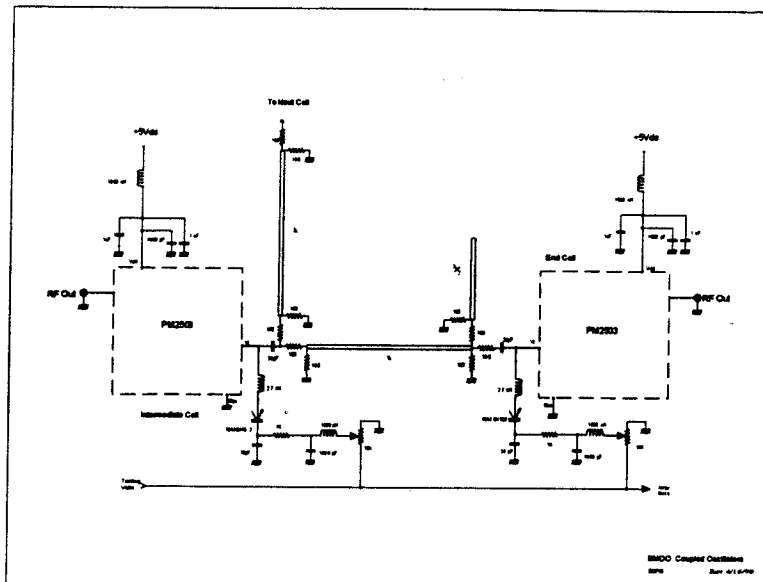
Description

The PM2503 is a GaAs negative resistance ("N-R") RFIC that requires only a 3.0 - 5.0 Volt bias and a 40mA supply current. An external varactor diode and spiral inductor provide a low cost oscillator solution while providing 14 dBm output power in the 2000 to 3000 MHz frequency range. The PM2503 contains a fundamental oscillator, integrated matching network, buffer amplifier and all bias networks. Potential applications include communication systems, transmitters, receivers, and other systems requiring a small easy to use source.

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With the consultation of the UCSB Group (R. A. York and P. F. Maccarini) the PM2503 RFIC was selected for use in constructing a laboratory model array at S-Band (2.5 GHz).

Partial Schematic

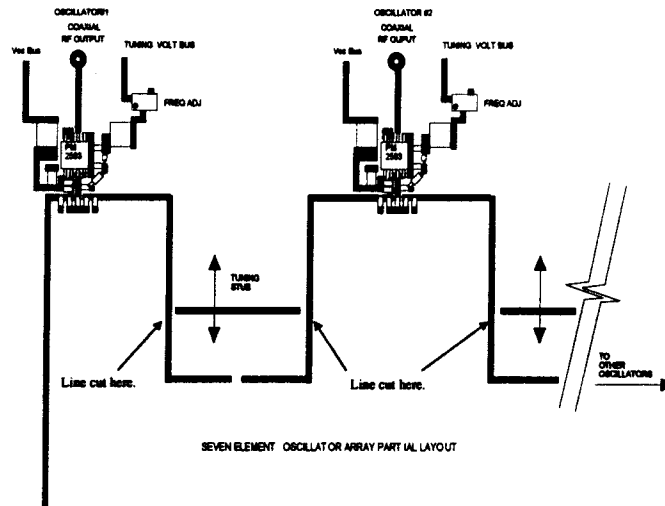


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This partial schematic shows one end oscillator and the adjacent one coupled with a 100 ohm transmission line one wavelength long. The 100 ohm termination resistors were included in an effort to reduce the Q of the coupler but, in retrospect the match between the oscillator and the line would have been better without them.

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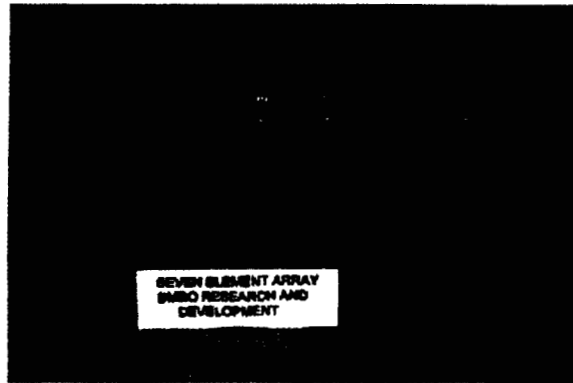
Partial Layout



This shows a portion of the board layout for the array including the coupling line arrangement which permitted variation of the line length to optimize the coupling phase. After the optimum was found by sliding the shorting bars, the bars were soldered in place and the lines were cut as shown.

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Seven Oscillator 2.5 GHz Array

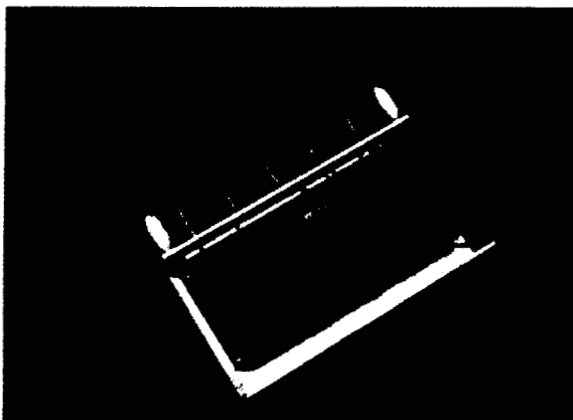


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The assembled oscillator array is shown here. The dip switches control the supply voltage to the oscillators so that they can be turned on or off in any desired combination. The shorting bars are not yet installed. The white binding posts are points at which the oscillator tuning voltage, controlled by a precision potentiometer, can be measured.

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Seven Element 2.5 GHz Oscillator Controlled Phased Array Antenna



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The shows the oscillator array mated with the seven element patch array. The shorting bars are clearly visible and the excess transmission line has been eliminated by cutting the line at the bar. There, of course, remains a discontinuity due to the difference in impedance between the line and the bar.

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Closeup of One Oscillator

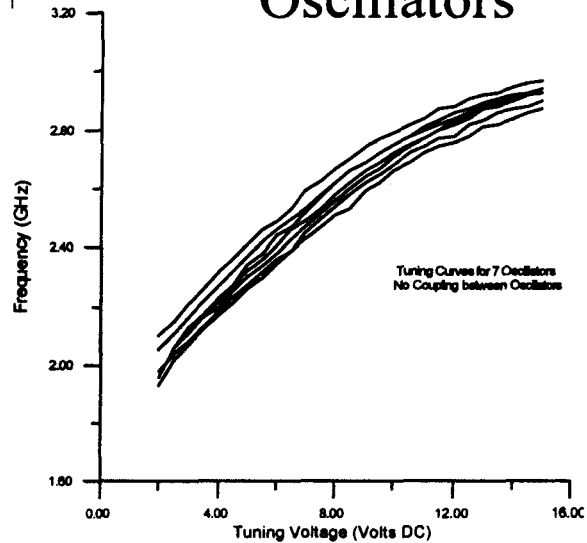


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This is a closeup of one of the oscillators showing the tuning potentiometer and binding post. Also visible are the inductors used to isolate the power supply from the rf.

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Tuning Curves for Uncoupled Oscillators

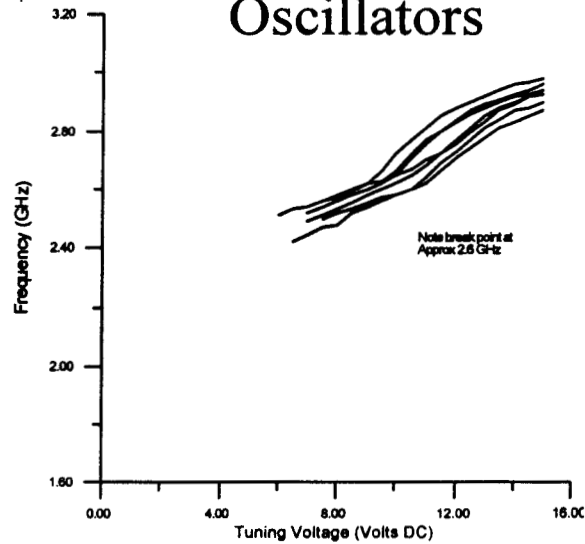


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The tuning curves of the oscillators when uncoupled are shown here. Note the spread in frequency for a given tuning voltage. Conversely, note the range of tuning voltages necessary to tune the oscillators to a given frequency. The tuning sensitivities (slopes), however, are very similar.

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Tuning Curves for Coupled Oscillators



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When the oscillators are coupled via the transmission lines, the tuning curves are modified as shown here. The linear portion at the lower end is the region of injection locking. The high end remains essentially unchanged from the uncoupled characteristics. The curves end where the oscillators stop oscillating. Thus, it is seen that the useful frequency range is from a little above 2.5GHz to about 2.6 GHz. Below this range one or more oscillators cease to function while above this range one or more oscillators lose lock.

Coupling Phase Effects

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},i} - \sum_{\substack{j=1 \\ j \neq i}}^{N+1} \Delta\omega_{\text{lock},ij} \sin(\Phi_{ij} + \theta_i - \theta_j)$$

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},i} - \sum_{\substack{j=1 \\ j \neq i}}^{N+1} \Delta\omega_{\text{lock},ij} [\sin(\Phi_{ij}) \cos(\theta_i - \theta_j) + \cos(\Phi_{ij}) \sin(\theta_i - \theta_j)]$$

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},i} - \sum_{\substack{j=1 \\ j \neq i}}^{N+1} \Delta\omega_{\text{lock},ij} [\sin(\Phi_{ij}) + \cos(\Phi_{ij})(\theta_i - \theta_j)]$$

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},i} - \sum_{\substack{j=1 \\ j \neq i}}^{N+1} \Delta\omega_{\text{lock}} [\sin(\Phi) + \cos(\Phi)(\theta_i - \theta_j)]$$

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The theory predicts some interesting relations between the coupling phase on the one hand and the array locking range and ensemble frequency on the other.

Beginning with the system of nonlinear first order differential equations presented by York one can use trigonometric identities to identify these effects.

Coupling Phase Effects (Cont.)

$$\theta_i = \omega_{ref} t + \phi_i$$

$$\frac{d\phi_i}{dt} = \omega_{tune,j} - \langle \omega_{tune,i} \rangle - \sum_{\substack{j=i-1 \\ j \neq i}}^{i+1} \Delta\omega_{lock} [\sin(\Phi) + \cos(\Phi)(\phi_i - \phi_j)]$$

$$\frac{d\phi_i}{dt} = (\omega_{tune,j} - \langle \tilde{\omega}_{tune,i} \rangle) - \sum_{\substack{j=i-1 \\ j \neq i}}^{i+1} \Delta\tilde{\omega}_{lock} (\phi_i - \phi_j)$$

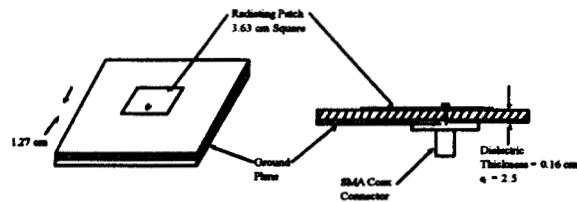
$$\langle \tilde{\omega}_{tune,j} \rangle = \langle \omega_{tune,j} \rangle + \Delta\omega_{lock} \sin(\Phi) \quad \Delta\tilde{\omega}_{lock} = \Delta\omega_{lock} \cos(\Phi)$$

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Defining the phase relative to a reference frequency, one can group terms and factors so as to define an effective ensemble frequency and effective locking range as shown. Note that the locking range is maximum when the coupling phase is a multiple of pi in which case the ensemble frequency is equal to the average of the free running frequencies.

These effects were easily observed during the shorting bar adjustment.

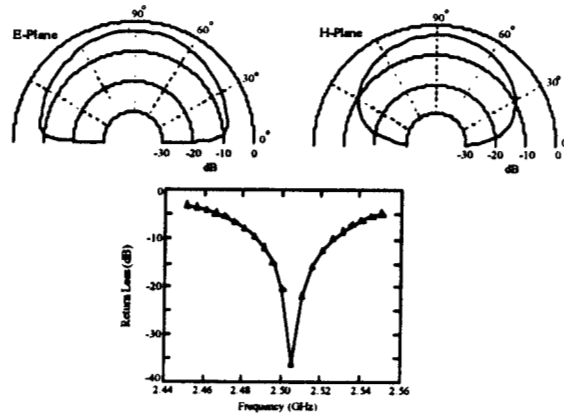
Design of the Patch Element



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This diagram shows the details of the design of the patch elements for the S-Band radiating aperture. They were designed to resonate at 2.5 GHz but, due to the tuning characteristics discussed earlier, the array was operated at 2.53 GHz resulting in a mismatch. This was mitigated by insertion of 10 dB pads behind the elements.

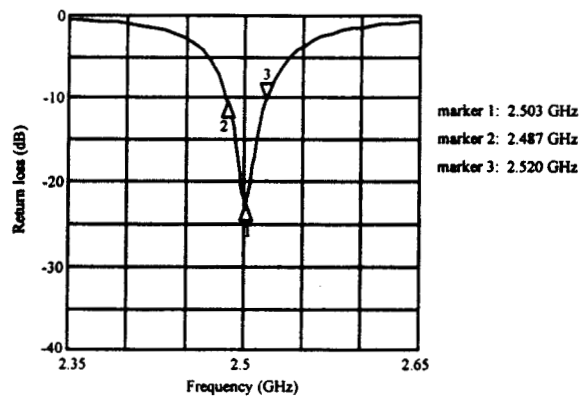
Calculated Pattern and Return Loss of Element



This shows the theoretical performance expected from the patch elements.



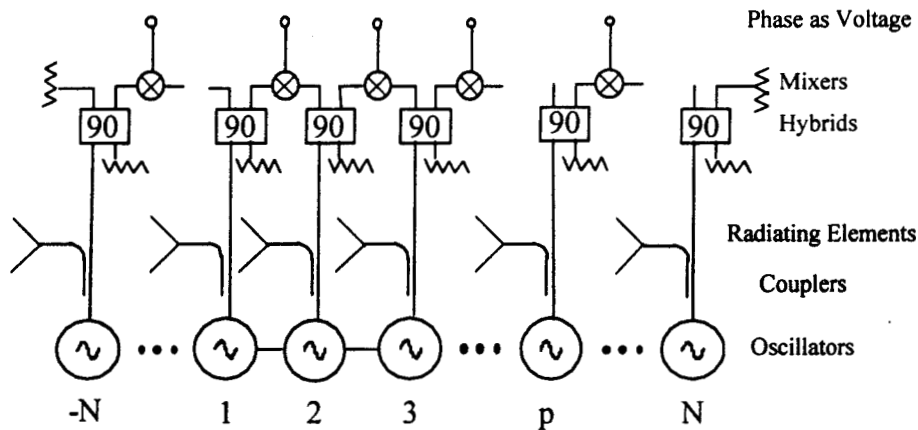
Measured Return Loss of Element



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This measured return loss agrees quite well with the theoretical prediction.

Mixers as Phase Detectors

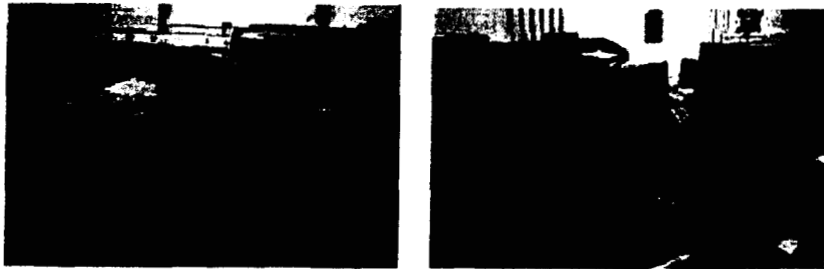


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The experimental setup for verifying the theoretically predicted array behavior makes use of mixers as phase detectors as shown here. The 90 degree hybrids are used to make the mixer outputs zero when the corresponding two oscillators are in phase. (Without the hybrids, the output would be zero for a 90 degree phase difference.) Ten dB couplers are used to derive the signals to be sent to the radiating elements. While one might expect that the mixer signals would be derived in this manner instead, the present arrangement provides adequate signal for driving the mixers while retaining the ability to measure radiation patterns since the receiver is more sensitive than the mixers.

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Laboratory Setup

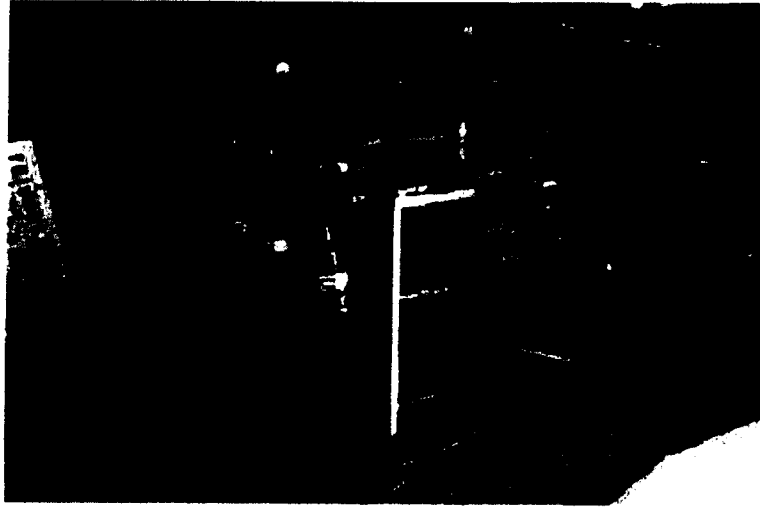


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This is a photograph of the laboratory equipment used to diagnose the array behavior.

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Diagnostic Circuitry

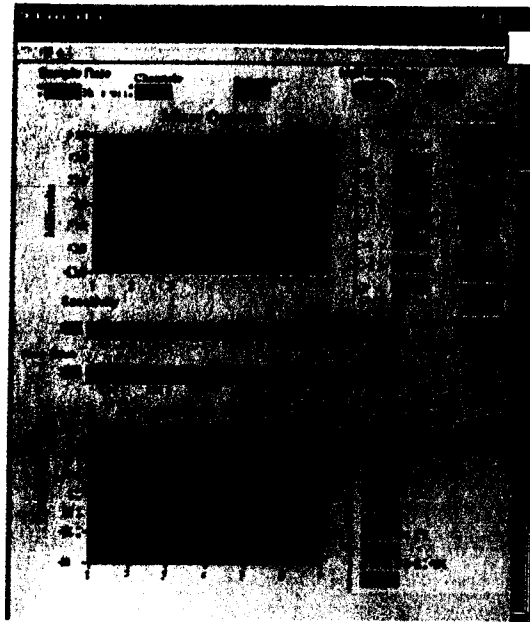


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This is a photograph of the array with the added diagnostic circuitry.

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Virtual Instrument Display (In-phase Case)

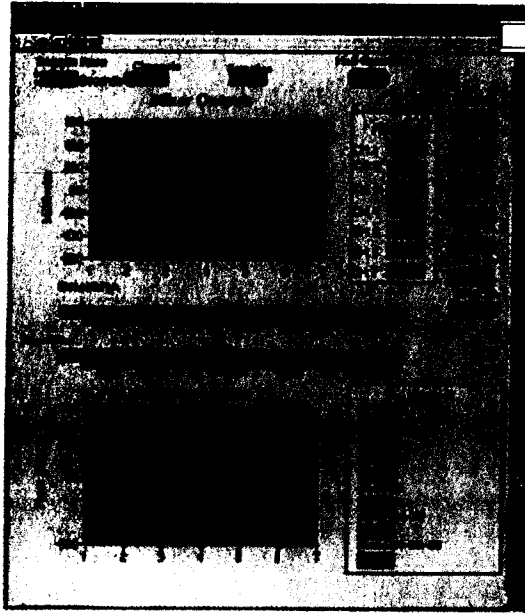


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The mixer outputs are read by a "Virtual Instrument" implemented in LabView. The display is shown above for tuning which yields a uniform aperture phase distribution.

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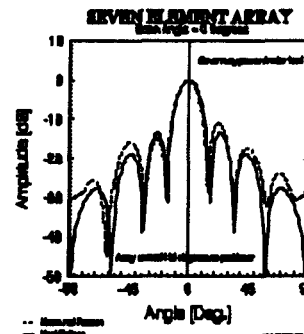
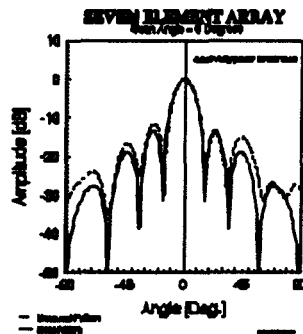
Virtual
Instrument
Display
(Linear Phase
Case)



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If the end oscillators are detuned oppositely, a linear phase distribution results as shown here.

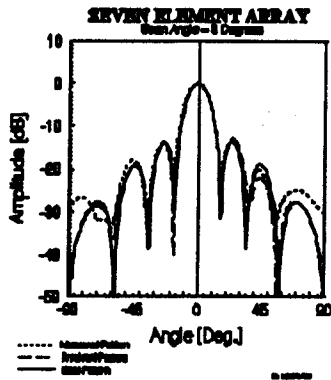
Array Pattern using Power Divider



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As a test of the radiating aperture, uncontaminated with coupled oscillator array effects, a pattern was measured with the aperture excited via an eight way power divider with one port terminated and the other seven connected to the patch elements. A second pattern was measured with the array rotated 180 degrees about boresight to discern possible range effects. These graphs compare the measured patterns with the theoretical ideal. The agreement is quite satisfactory and range artifacts are only evident below -25 dB.

Zero Degree Scan

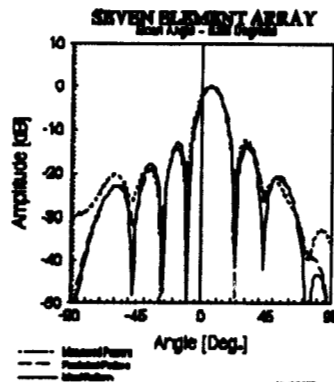


Osc.	Freq. (GHz)	Pwr (dBm)	Tuning Voltage	Phase (Deg.)
1	2.530	-9.67	7.39	0.0
2	2.530	-9.90	8.40	-4.9
3	2.530	-9.17	9.65	-6.7
4	2.546	-10.00	6.99	6.8
5	2.530	-9.17	8.01	0.0
6	2.530	-8.83	8.29	-5.6
7	2.530	-10.83	8.72	2.3

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Three patterns are shown here for zero degree scan. The solid line is the ideal pattern of the seven element array. The dashed line is the pattern predicted from the measured amplitude and phase of the patch excitations shown in the chart. Finally, the dotted line is the measured pattern under oscillator excitation of the patch array.

6.38 Degree Scan

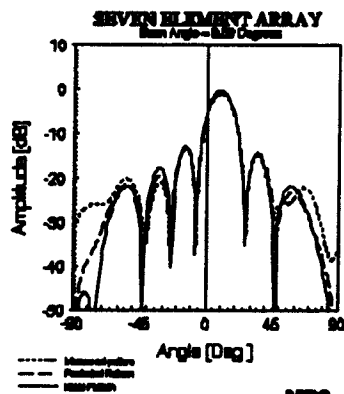


Osc.	Freq (GHz)	Pwr (dBm)	Tuning Voltage	Phase (Deg.)
1	2.547	- 9.00	7.89	0.0
2	2.530	- 9.67	8.40	- 32.2
3	2.530	- 9.50	9.65	- 65.5
4	2.546	-10.00	6.99	- 99.6
5	2.530	- 9.17	8.01	- 83.6
6	2.530	- 9.00	8.29	-106.5
7	2.519	-10.83	8.50	-121.7

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These curves are similar to those in the last vugraph but, this time, for a scanned beam. As can be seen from the chart this scan was achieved by changing the tuning voltage on the end oscillators.

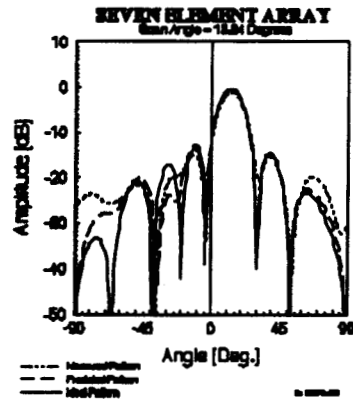
9.59 Degree Scan



Ch.	Freq. (GHz)	Pwr (dBm)	Tuning Voltage	Phase (Deg.)
1	2.553	-8.83	8.03	0.0
2	2.530	-9.67	8.40	-37.0
3	2.530	-9.50	9.65	-63.4
4	2.546	-10.17	6.99	-99.7
5	2.550	-9.17	8.01	-123.5
6	2.530	-9.17	8.29	-153.0
7	2.514	-11.17	8.57	-179.5

Here the tuning voltages are further adjusted to produce a larger scan angle.

12.84 Degree Scan

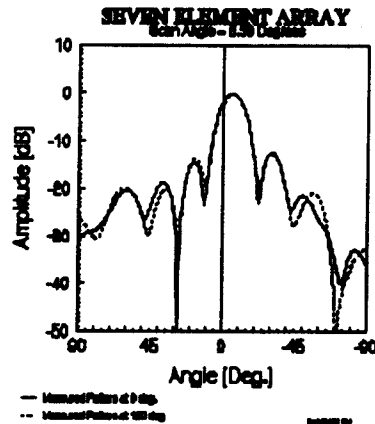


Osc.	Freq. (GHz)	Par (dBm)	Tuning Voltage	Phase (Deg.)
1	2.554	-8.83	8.07	0.0
2	2.530	-9.67	8.40	-49.4
3	2.530	-9.50	9.63	-71.6
4	2.546	-10.33	6.99	-128.0
5	2.530	-9.17	8.01	-156.0
6	2.530	-9.50	8.29	-192.0
7	2.486	-12.50	7.95	-242.0

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This final scan case shows the beam nearly 13 degrees off boresight. Beyond this point, the amplitude of oscillator number 7 drops to too low a level to participate in the interaction and loses lock.

Range Assessment



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Lastly, a range assessment was carried out by rotating the array 180 degrees about the boresight with the beam scanned to 6.38 degrees. This shows that range artifacts are negligible above the -20 dB level.

Concluding Remarks

- A coupled oscillator controlled phased array has been designed, fabricated, and evaluated.
 - PM2503 oscillators MMICs
 - Seven patch elements
 - Linear (one dimensional) array
 - Transmit only
- The theoretical predictions of coupling phase effects were verified.
- The beamsteering range was limited by amplitude variation with tuning.

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While this array is transmit only, a receive array can be designed using the same principles. One would use the oscillators of the array to provide local oscillator signals to be mixed with the signals from each receive element in the aperture. These local oscillator signals would carry the phase necessary to render the received signals cophasal for incidence from a given direction. The direction is, of course, determined by detuning the end oscillators of the array just as in the transmit case.